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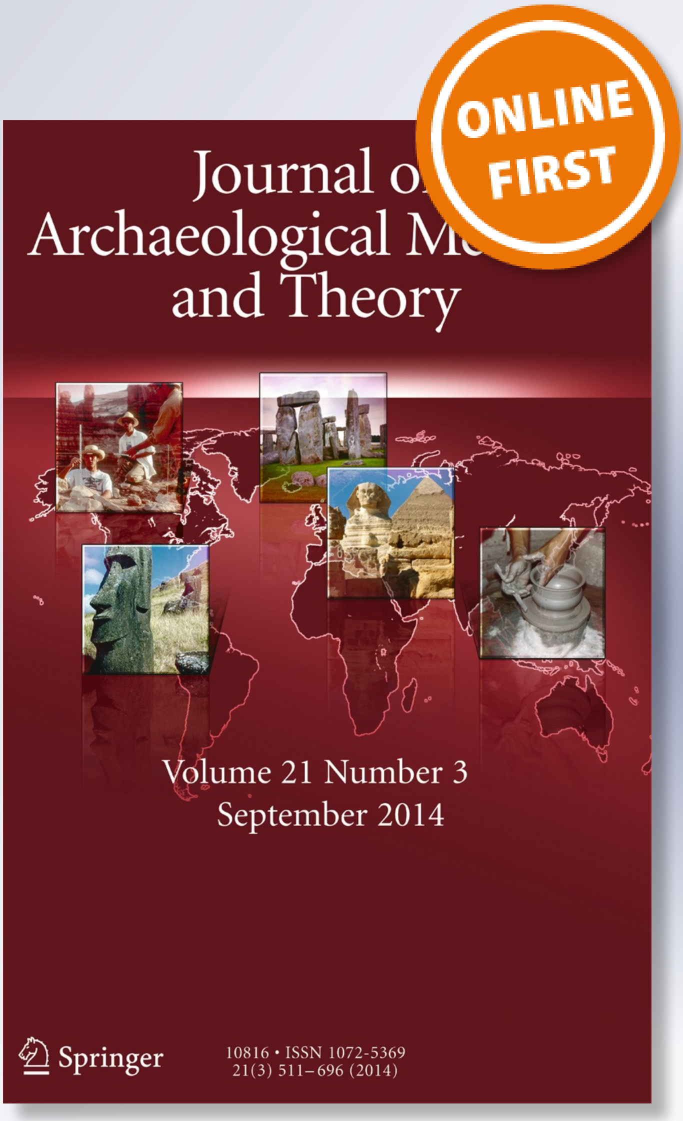

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# The Spatial Structure of Lithic Landscapes: the Late Holocene Record of East-Central Argentina as a Case Study

**Gustavo Barrientos · Luciana Catella · Fernando Oliva**

**Abstract** The aim of this paper is to discuss conceptual and methodological issues related with the archaeological study of lithic landscapes and exemplify the approach with a case study (artifact distribution data from east-central Argentina). A lithic landscape—understood as the co-occurrence, in a given geographic space, of different structural units each one composed by a raw material source and the complete set of unmodified and human-modified pieces of rock extracted from that source and then transported, used, and discarded across the landscape (*i.e.*, a scatter area)—can be modeled using kriging, a geostatistical interpolation tool useful for integrating scattered information into coherent spatial models. The case study allows for the examination and discussion of, on one hand, the relationships between the type and location of the

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sources and the size and shape of the respective scatter areas and, on the other, the reciprocal relationships between different raw materials and sources. It is concluded that a proper description of the spatial structure of a lithic landscape is the needed baseline from which to evaluate different explanatory models. Such models should take into account different sets of initial conditions and generative mechanisms, in order to cope with the pervasive problem of equifinality.

**Keywords** Lithic landscapes · Raw material sources · Artifact distributions · Geostatistics · East-central Argentina · Late Holocene

## Introduction

A spatial structure can be conceptualized as a patterned arrangement of entities in an *n*-dimensional space. From a geographic point of view, the term usually refers to the organized distribution of objects on, or immediately beneath, the surface of the earth. Spatial structures exist because geographic space (*i.e.*, macroscopic, large-scale space; Jiang 2010) is not homogeneous but composed of a set of variously distributed unique places and features (Elissalde and Saint-Julien 2004). Indeed, geographic spaces tend to be heterogeneous and structured, with such qualities emerging from both deterministic and stochastic processes. At the spatial scales at which human social or population phenomena usually occur (micro-, meso-, and macroscales; Delcourt and Delcourt 1988; Dincauze 2000), the geographic space is heterogeneous relative to many significant objective and subjective, intrinsic and extrinsic variables, like distribution, diversity, density, predictability, availability, accessibility, attractiveness, or yield of a resource. In the case of prehistoric hunter-gatherer populations, the distribution, availability, accessibility, quality, and exploitability of lithic raw materials (Ataman *et al.* 1992; Bamforth 1986; Elston 1992; Kuhn 1991; Wilson 2003, 2007a, b, 2011) were likely major socioecological factors either constraining or allowing the spatiotemporal material expression of their aggregated (*i.e.*, individual plus collective) behaviors. On the long run, the cumulative effects of spatiotemporal behaviors (*i.e.*, individual and collective behaviors that manifest at different successive points in space and time) involving the procurement, manufacture, transport, use, and discard of lithic materials provide the structural features of what we can call a lithic landscape (*cf.* Gould and Saggers 1985, p. 124). Such a landscape can be ideally thought as the spatial co-occurrence of different structural units (*i.e.*, the “building blocks” of the larger structure that is the lithic landscape), each one composed by two principal elements, a raw material source and a surrounding scatter area, the latter comprising the complete set of unmodified and human-modified pieces of rock extracted from that source and then transported, used, and discarded across the landscape. Lithic landscapes can be archaeologically approached using a variety of sampling, analytical, and visualizing techniques. The construction of reliable models about the spatial structure of such landscapes should be the first step of any research aimed at understanding, at some specified scale, the relationships between the organization of the archaeological record (our subject matter) and the organizing dynamics that operated in the past (our explanatory variables). Those dynamics primarily include, at the ecological time, the successive choices of social actors obeying to certain logics (Clark and Scheiber 2008; Elissalde and Saint-Julien 2004), although it is expected that, on the long run (*i.e.*, at evolutionary time), the overlapping and commingling effects of a variety of such logics and of other factors—*e.g.* taphonomic and, at a later stage, archaeological (sampling and analysis)—will hamper a straightforward lecture of the material and relational evidence in terms of identifiable systemic—mainly behavioral—processes (Barton *et al.* 1999, 2002, 2004; Bailey 1981, 2007; Burger *et al.* 2008; Holdaway *et al.* 2008, 2012; Shott 2006; Wandsnider 1992, 1998; Wilson 2007b; Zvelebil *et al.* 1992).

Within this context, the aim of this paper is twofold: first to set the background for the study of the spatial structure of lithic landscapes, discussing—in a programmatic way—the theoretical, methodological, and epistemological foundations for its archaeological study; second, to exemplify the approach to the description (*i.e.*, spatial modeling) of lithic landscapes with a case study involving artifact distribution data from east-central Argentina. The detailed discussion of many specific aspects of the lithic record from this region is out of the scope of this paper and is addressed elsewhere (Catella 2014). However, it is expected that the data and analyses presented in this exploratory study will illustrate well both the strengths and limitations of the advocated approach, thus encouraging future theoretical, methodological, and empirical research on the subject.

## What Is a Lithic Landscape?

### A Concise Definition

Among the many existing archaeological perspectives on landscape, in this paper, we adopt the one that considers it an efficient means of representing and understanding spatiotemporal variability in the archaeological record (Holdaway *et al.* 2012). The active incorporation of space in the analysis allows for the integration of a diversity of datasets and for a better approach to the processes that produce, at different scales, the kind of patterned variation whose documentation and explanation constitutes one of the core objectives of archaeological research (Binford 2001; Darvill 2008; Kelly and Thomas 2009).

From this perspective, a lithic landscape would be conceptualized as the co-occurrence, in a given geographic space, of different structural units composed by two principal elements: a raw material source and an associated scatter or strewn area. The latter comprise the spatial distribution of both unmodified and human-modified pieces of rocks, either directly or indirectly (Féblot-Augustins 2009) procured from that source (Fig. 1). This is a different and a more inclusive definition of the term than that first introduced in the literature by Gould and Saggers (1985). For these authors, a lithic landscape refers solely to the availability and physical distribution of different raw materials in a region (Gould and Saggers 1985, p. 124), thus being equivalent in meaning to the terms “regional lithic resource base” (Ericson 1984) and “lithic terrane” (Elston 1992).

### The Components of a Lithic Landscape

Lithic raw materials can come from either point or diffuse sources. A point source is a localized and a more or less isolated primary (*e.g.,* a bedrock exposure or outcrop) or secondary (*e.g.,* a glacial, stream, beach, and talus slope deposit) procurement place (the “primary” and “secondary” character of sources coincides here with the definition

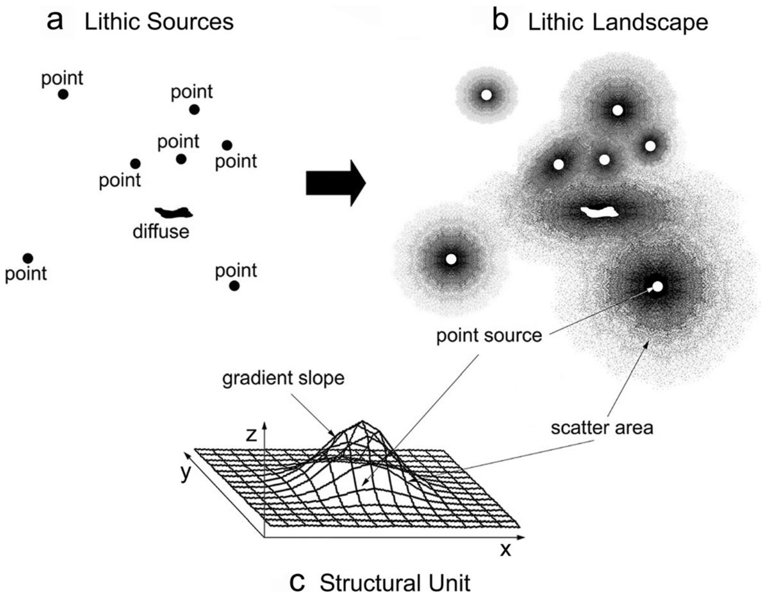

**Fig. 1** Schematic representation of the structure of a lithic landscape. **a** Point and diffuse sources of a particular raw material; **b** sources and scatter areas; **c** 3D view of a structural unit in which $x$ and $y$ represent space and $z$ the value of a response variable (*e.g.*, raw counts, percentages, or frequency data)

of "primary" and "secondary" geological contexts; Luedtke 1979, p. 745; for a different and less usual definition of primary and secondary lithic sources, see McCoy *et al.* 2010, p. 174). A diffuse source (Bakken 2011) is a very extensive (*i.e.*, ranging from the local to the regional domains) and a difficult-to-delimit procurement area, in which toolstones are available in either a primary (*e.g.*, a large-scale geologic formation) or a secondary (*e.g.*, a geographically extended gravel mantle, or a glacial drift deposit) geological context.

While the concept of source is rather unproblematic, with a large amount of literature dealing with the subject (*e.g.*, Ataman *et al.* 1992; Bakken 2011; Bamforth 2006; Blades and Adams 2009; Charlin 2009; Colombo 2013; Elston 1992; Ericson and Purdy 1984; Franco and Borrero 1999; Gould and Saggers 1985; Ingbar 1994; Kuhn 1991; Luedtke 1979; Topping and Lynott 2005; Torrence 1986, 1989; Wilson 2007b, 2011), the introduction of the concept of scatter area requires some justification. The basic premise lying behind the concept is that the operation of any system based on the exploitation of lithic resources will produce—at different temporal scales—a spatial rearrangement of rocky fragments either under the form of raw materials (*i.e.*, unmodified chunks/hunks/sheets/chips; Greber 1976) or artifacts (*i.e.*, cores, tools, and debitage) with the latter in turn potentially serving, due to the extractive nature of lithic technology, as raw materials for further artifact production (see, among others, Collins 1975; Ericson 1984; Kelly 1988; Kuhn 1991; Nelson 1991) . This implies that there is always a spatial transfer of rocks from an exploited source to one or many other locations across the landscape as the result of the operation of such a system (*e.g.*, Féblot-Augustins 2009; Renfrew 1972). The implied transport of unmodified and human-modified stones can be very short (less than 1 m) or very long (of the order of hundreds or even thousands of kilometers). The spatial distribution of all the unmodified rocks and artifacts deposited on or beneath the earth's surface and whose raw materials come from a single source defines a scatter or strewn area. This term ought not to be confused with that of "lithic scatter," which is defined as a type of archaeological site (*i.e.*, a microscalar phenomenon) consisting in a surface distribution of lithic artifacts primarily resulting from the disturbance of original depositional contexts by natural forces and/or human agency (Chartkoff 1995, p. 29; English Heritage 2000, p. 2).

It is important to note that we never have neither a direct nor a complete access to the nature of a scatter area. Just like in the case of settlement patterns—where archaeologists do not have access to the full set of places used by an organized group of people at some specified time period in the past but only to a limited number of such places, *i.e.*, to a "remnant settlement pattern" from which some properties of the "full settlement pattern" ought to be inferred (Rouse 1972, p. 97)—all the characteristics of a scatter area have to be modeled from archaeological evidence.

Ideally, a scatter area around a raw material source can be regular (*i.e.*, near-symmetric) or irregular in shape (Ericson 1977). Its extension can be variable, but usually comprising sizes belonging to a meso- or a macroscale spatial domain (see Delcourt and Delcourt 1988; Dincauze 2000). An important property of a scatter area is gradient, which designates the usually (but not exclusively) monotonic decrement (Renfrew 1972, 1975, 1977; Renfrew *et al.* 1968; *cf.* Ortega *et al.* 2014)—alternatively called fall-off or distance decay—in spatial density, size, weight, or frequency of lithic artifacts from the raw material source to the outer limits of the strewn area (Fig. 1). This is a well-known pattern affecting different commodities and products that emerges because the costs of transport usually increase with increasing distance from the source. [1] Such a gradient can be smooth or steep depending on factors like mobility patterns, the quality of the raw material, the nature of the access to the commodity (direct o indirect *via* exchange or trade), and the spatial proximity and/or competition[2]—in terms of human needs, preferences, and strategic/tactical/operational decision rules—between two or more raw material sources (Biró and Regenye 1991; Brantingham 2006; Elston 1992; Ericson 1977; Hodder and Orton 1976; Kooyman 2000; Reid 1986; Torrence 1986; Wilson 2007b).

It can be predicted that, around an isolated source and over a featureless isotropic plain, the corresponding scatter area will take—on the long run—a round shape with a radially symmetric distribution of gradient. This is so because the successive movements (and the consequent transport and discard of toolstone) from that source to outer areas will occur with equal probability in all directions, a process that can be easily

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[1] People, of course, do not necessarily make decisions based on cost considerations. However, the probability of transporting a certain quantity of raw materials under the form of artifacts or unmodified pieces of rock (objects with mass, and hence with weight) decreases as a function of the distance from the source, irrespective of the conscious or unconscious decisions of the actors. In the short term, we may observe significant deviations from the expected distance decay pattern, but on the long run, the cumulative distribution of lithics across a region resulting from a large number of events of transport, use, and discard will tend to statistically manifest the influence of this natural organizing principle.

[2] When we speak of "competition" between rocks, we are using a figurative expression to depict a situation in which two or more toolstones, whose sources are spatially close to one another, have a differential probability of being used by humans. Such a probability depends on the intrinsic properties of the rocks and of their sources but, above all, on cultural preferences and strategic/tactical/operational decision rules applied by people. With the same or nearly the same meaning, the term has already been used by several authors (*e.g.*, Biró and Regenye 1991; Laylander 2005; Shelford *et al.* 1982; Tripcevich 2007).

simulated with random walks (Brantingham 2006; Hodder and Orton 1976). In most real situations, however, there are a number of factors that may create deviations from an ideal symmetric distribution (Haggett 1965; von Thünen [1826] 1966). Foremost among them is the presence of competing or alternative raw material sources and of landscape features that modify, either by increasing (*e.g.*, upland areas of difficult terrain) or diminishing (*e.g.*, navigable rivers, corridor areas), transport costs (Fig. 2).

## The Palimpsest Nature of Lithic Landscapes

Rocks from two or more sources can travel together (*i.e.*, integrating specific toolkits) or separated, but however, they can be discarded, cached, or lost at the same place in a single or different events (Barton *et al.* 1999, 2002, 2004; Wandsnider 1992, 1998; Wilson 2007b; Zvelebil *et al.* 1992). Rocks from different sources can accumulate at any given point in space at different rates, then producing a differential representation of each toolstone class. This is a process controlled by the influence of many different factors primarily related to (a) the rocks themselves (*e.g.*, regional abundance, mechanic properties, size, shape, and location of the outcrops or secondary deposits; Ataman *et al.* 1992; Brantingham *et al.* 2000; Ingbar 1994; Kuhn 1991; Wilson 2007b); (b) human organization and demography (*e.g.*, geographic distribution of people and population density values, kind and degree of mobility; Ataman *et al.* 1992; Binford 1980; Brantingham 2003, 2006; Chatters 1987; Jeske 1992); and (c) culturally inherited preferences and decision rules related with different aspects of the organization of technology (*e.g.*, distance between loci of human activity and raw material sources, portability of the different products of a particular reduction sequence, rock quality judgments, design constraints and possibilities, degree to which a specific toolstone is laden with cultural or prestigious associations; management strategies of lithic resources, including the control on the access to the sources, the transport and caching of chunks or artifacts, the exchange or trading of lithic materials, levels of planning, provisioning strategies; *e.g.*, Amick 1996; Bamforth 1986; Bamforth and Woodman 2004; Binford 1973, 1977, 1979; Brantingham 2003, 2006; Carr and Bradbury 2011;

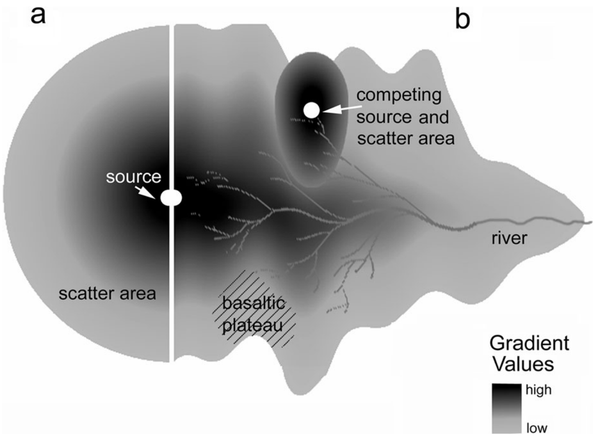

**Fig. 2** 2D representation of a structural unit of an ideal lithic landscape. *a* Round scatter area with a radially symmetric distribution of gradient around an isolated source and over a featureless isotropic plain; *b* irregular scatter area in a heterogeneous landscape surface

Chatters 1987; Collins 1975; Elston 1992; Graf 2010; Hodder and Orton 1976; Ingbar 1994; Kelly 1988; Khun 1995, 2004; Nelson 1991; Renfrew 1977; Roebroeks *et al.* 1988; Tripcevich 2007; Wilson 2007a, b, 2011). In archaeological time, however, the effects of all these factors operating at the systemic level (*i.e.*, in the short to medium term) usually clump together forming inextricable palimpsests (*e.g.*, Aston and Rowley 1974; Bailey 1981, 2007; Binford 1980, 1981; Holdaway *et al.* 2008; Ferring 1986; Wandsnider 1998). Since its popularization by Binford (1981), the notion that the palimpsest effect constitutes one of the main structural properties of the archaeological record has become firmly established, being one of the fundamental concepts of time perspectivism (Bailey 1981, 2007; Holdaway *et al.* 2008). A palimpsest is the natural consequence of the accumulation of materials deposited, at different rates and at different scale domains (*i.e.*, micro-, meso-, and macroscale, roughly corresponding to the local, regional, and supra- or macroregional levels, respectively), in the course of multiple successive episodes occurred at both particular activity areas and transit corridors or paths connecting such areas, whose spatial position changes over time. From the viewpoint of time perspectivism, the one that we favor, palimpsests are conceived not as a kind of "noisy" structure that needs to be dissected and disentangled, but as the consequence of processes that create—at different scales—temporospatial patterning in the archaeological record (Holdaway *et al.* 2008). An archaeological approach to lithic landscapes thus involves the problem of extracting meaningful information (in terms of the understanding of long-term processes) from the cumulative patterning of the material correlates of human behavior, an issue that is addressed in the next section of this paper.

## The Archaeological Study of Lithic Landscapes

### Descriptive/Interpretive Modeling

### *The Regional Lithic Resource Base and the Problem of Sourcing*

The size of the geographic space at which the structure of lithic landscapes ought to be modeled, ranges from the mesoscale to the macroscale (*i.e.*, regional to supraregional level of analysis). Within such spaces, the assessment of the absolute and relative position of two kinds of elements is crucial, namely (i) the potential and actual sources of lithic raw materials, and (ii) the unmodified and human-modified pieces of rock coming from those sources and whose presence in specific points of the landscape cannot be explained by forces other than human agency. This presupposes the carrying out of systematic activities aimed, first, at assessing the structure of the regional lithic resource base (*sensu* Ericson 1984) and then at sourcing—*i.e.*, the act of establishing a hypothetical linkage between (a) single isolated elements or set of elements and (b) variously defined raw material sources (Bishop 2012, p. 579).

The building of reliable models about the structure of a regional lithic resource base is a complex undertaking that requires the integration of multiple sources of information (*e.g.*, geological, geomorphological, petrographic, geochemical, archaeological), the execution of different activities (*e.g.*, bibliographic and cartographic search, field survey, remote sensing, laboratory analysis, interdisciplinary interaction), and the acquisition, administration, analysis, and graphical representation of a high volume of spatial data. The resulting model—which is always provisional and perfectible—can have, at different scales, a various degree of detail and resolution due to insufficient or imperfect information. In general, such a model is based on actualistic information, and there is no simple way to assess the past availability, abundance, form, quality, and exploitability of lithic resources, particularly for environments that have experienced significant geomorphological change (Phillips 2011). Despite this, it is clear that all effort invested in assessing the structure of the regional lithic resource base is worthy since it constitutes a major factor influencing the way stone tools were produced, transported, used, maintained, and discarded (Andrefsky 2009).

The knowledge about raw material sources is just a part of the problem, to the extent that it is almost useless unless we are able to establish clear, albeit hypothetical, connections between sources and products (*i.e.*, artifacts recovered at different locations across the landscape). Several methods exist to accomplish this task, being the visual assessment of hand specimens the commonest sourcing practice everywhere (Andrefsky 2009; Elburg and van der Kroft 2006; Odell 2004). This is so because more precise options, like petrographic (*e.g.*, thin-section microscopy, X-ray diffraction or XRD) or geochemical methods (*e.g.*, acid digestion and laser ablation inductively coupled plasma mass spectrometry or AD-ICP-MS and LA-ICP-MS, respectively), still remain difficult to implement at large scale due to a number of reasons (*e.g.*, limited time and budget, restricted access to appropriate facilities, lack of specific training; see discussion in Odell 2004, pp. 41–42). However, despite the many advances in sourcing methodology, it must be remembered that not all toolstone can be sourced with equal confidence. There seems to be a close inverse relationship between the degree of complication of the rock formation process (including its duration and spatial extension) and the reliability of sourcing using geochemical techniques (*e.g.*, obsidians are more confidently linked to sources than cherts or quartzites; Andrefsky 2009, pp. 79–80; *cf.* Pitblado *et al.* 2013). In practice, all of these factors cause that, in a given region, a significant portion of the lithic assemblages recovered at archaeological sites can only be loosely linked with specific sources or cannot be sourced at all (Elburg and van der Kroft 2006). This is a major, yet unresolved issue with which archaeologists have to deal in more creative ways—beyond and besides technological sophistication—than those that are currently being used in studies of lithic raw material exploitation. In this sense, the spatial modeling of lithic landscapes can help, to some extent, to establish hypothetical connections between assemblages and sources as it will be shown later in this paper.

### *Artifact Distribution Data*

Regarding the spatial distribution of artifacts, two basic theoretical assumptions of landscape archaeology (broadly defined here as the archaeological subfield that addresses the issue of how past people have consciously and unconsciously shaped, for a variety of reasons, the land around them; Fennell 2010, p. 1; Hu 2011, pp. 80–81) are that human behavior has a rather continuous expression across space (Foley 1981, p. 13) and that their material products are consequently distributed in a more or less continuous fashion on the surface of the earth (Banning 2002, p. 15; Ebert and Kohler 1988, p. 143; Foley 1981, p. 13; Robins 1997, p. 26). The assumption of a rather continuous expression (both immaterial and material) of human behavior, particularly across space, is the main tenet of off-site or distributional archaeology (*sensu* Foley 1981; Ebert 1992). Individual and collective behaviors manifest themselves in a continuous (in the sense of nondiscrete) way both in space and in time. The material expression of such behaviors also tends, especially in the medium to long term, to be distributed more or less continuously (though with a remarkable variation in density) over the surface of the earth.

The survey strategy advocated by distributional archaeology—simple or stratified random sampling of the surface distribution of artifacts across large geographic spaces (Belardi 1992; Belardi *et al.* 1992; Borrero *et al.* 1992; Dunnell and Dancey 1983; Ebert 1992; Ebert and Kohler 1988; Foley 1981; Thomas 1975)—seems the most appropriate choice for data acquisition aimed at building continuous spatial models of lithic landscapes. However, this sampling approach can only be successfully implemented in regions of high archaeological visibility, which is greatest in areas of low/slow sedimentation, high deflation, and low vegetation cover. In regions characterized by higher rates of sedimentation, lower rates of soil erosion, and lower surface visibility due to dense ground cover, most of the survey effort at the meso- or macroscale is typically allocated to the searching of sites by nonprobability means (*e.g.*, convenience, opportunistic, or emergent sampling; Patton 2002). This occur despite of the theoretical/methodological awareness of the involved archaeologists and obeys to the fact that subsurface discovery techniques like shovel testing and ground penetrating radar assessment (GPR) are virtually impracticable at a higher-than-local level.

While relying on primary or original data may be desirable in order to model a lithic landscape—irrespective of the sampling procedure deployed in each case—it is highly unlikely that any single study can cover a space of the magnitude in which it really makes sense to speak of such an entity (*i.e.*, meso- to macroscale domains). As a consequence, the analysis of secondary data (*i.e.*, a research strategy which makes use of preexisting data for the purposes of investigating new questions or verifying previous studies; Heaton 2004, p. 16) is usually imposed as a necessity, not a choice.

The fact that quantitative and distributional data may come from a heterogeneous combination of survey strategies deployed at different times by different research teams (*i.e.*, the authors of the original reports) seems, at first glance, a limitation to the quality of data available to model lithic landscapes. However, if conveniently and appropriately filtered, secondary data can be very valuable to the extent that they provide effective means of approaching large-scale phenomena, applying new research questions, and gaining new insights and deeper understanding on old problems at a relatively low cost, measured in terms of time, effort, and loss of information (Andrews *et al.* 2012; Atici *et al.* 2013).

### *Spatial Analysis and Modeling*

Assessing the spatial structure of a specific lithic landscape heavily depends on the ability to manage a great deal of geographic information relative to the location of raw material sources (both primary and secondary), archaeological sampling units, relevant landscape features, and response variable values (*e.g.*, absolute or relative frequency, density, weight). Geographic information systems (GIS) are the natural tools to aid in this task. A GIS integrates hardware and software for capturing, managing, analyzing, and displaying different forms of geographically referenced information in search for relationships, patterns, and trends in data. It is, and has been for the last 20 years or so, a much used tool to map and analyze the spatial distribution of archaeological materials (Conolly and Lake 2006; Ebert 2004; Verhagen and Whitley 2012) across and along archaeological landscapes.

Among the many analytical devices incorporated into modern GIS is geostatistics, a multipurpose set of tools used for characterizing spatial variation. Geostatistics deals with the problem of how to make reliable predictions of sampled attributes at unsampled locations from sparse data (Burrough 2001) and is based on the principle of spatial dependence or autocorrelation, which establishes that observations close in space tend to be more similar than those further apart (*i.e.*, the so-called first law of geography; *sensu* Tobler 1970; see also Lloyd and Atkinson 2004, p. 151; Miller 2004, p. 285). A prominent procedure in geostatistics is interpolation, which is the estimation of the value of a variable at an unmeasured location from observed values at surrounding locations. Interpolation is a method of constructing new data from a discrete set of known data points, enabling the translation of sampled point data into continuous surfaces (Conolly and Lake 2006; Hodder and Orton 1976; Lloyd and Atkinson 2004; Miller 2004). The examination and analysis of continuous surfaces—a procedure that already has a long history in archaeology (*e.g.*, Biró 1998; Biró and Regenye 1991; Ericson 1977; Findlow and Bolognese 1982; Hodder and Orton 1976)—makes more intelligible the spatial information recovered from relatively few, scattered, and unevenly distributed sampling locations.

The geostatistical interpolation tool is kriging, a group of techniques that uses semivariogram (*i.e.*, a two-point statistical function that describes the decreasing correlation between sample values as spatial separation between them increases) to express the spatial variation in data. Technically defined, kriging is an optimal interpolation method based on regression against observed $z$ values of surrounding data points, weighted according to spatial covariance values. The kriging techniques offer a number of output surface types like prediction, prediction standard error, quantile, and probability maps (Johnston *et al.* 2001), which are major features that distinguish them from deterministic methods for spatial interpolation like inverse distance weighting (IDW) and splines (Azpurua and Dos Ramos 2010; Burrough and McDonnell 1998; Villatoro *et al.* 2008). Originally introduced in the archaeological literature by Zubrow and Harbaugh (1978), kriging methods have been used in recent years to represent artifact distribution data at different spatial scales and for different purposes (*e.g.*, Aldenderfer 1998; Bevan and Conolly 2009; Harro 1997; Lloyd and Atkinson 2004; Mullett 2009, 2012; Skarbun and Frank 2011).

In order to illustrate the power of kriging to generate reliable models of an underlying spatial structure, we performed a set of informal (*i.e.*, not statistically validated) simulations varying the number and distribution of sampling units superimposed to an ideal graphic depiction of a lithic landscape (Fig. 3). In such representation, different shades of gray symbolize different values of a variable (*e.g.*, raw counts) measured on artifact samples made with a single raw material coming from eight sources. In our ideal model, there is a continuous monotonic decrease in absolute frequency values from the source to the outer limits of the surrounding scatter area. In the first simulation, the sampling units ($n$=437) were arranged in a regular grid, whereas in the second one, a lesser number of sampling units ($n$=154) were irregularly distributed. In both cases, the data collected from each sampling unit were entered into a spreadsheet and analyzed with the use of ArcGIS 9.3, allowing for the creation of a continuous interpolated surface (prediction map) applying kriging. Figure 3 shows that, in the case of a regular and uniform distribution of a great number of sampling units, the surface map generated by kriging reveals very well the underlying structure of the lithic landscape. By contrast, in the case of a lesser number of irregularly distributed sampling units, the corresponding surface map allows us to glimpse in a somewhat distorted way—something like through a frosted glass—the spatial configuration of the underlying structures. Despite this fact, it is significant that the resulting surface is still informative about the main features of the target lithic landscape. This is remarkable since, in most real-world situations, it is highly likely that both the number and distribution of sampling units will resemble the second rather than the first simulated example.

It has been experimentally shown (Milillo and Gardella 2005) that, with few data points, IDW yield better results than kriging in terms of providing spatial models that capture more details from an underlying image. However, as it was already mentioned, kriging has many comparative advantages over other interpolation methods (*e.g.*, built-

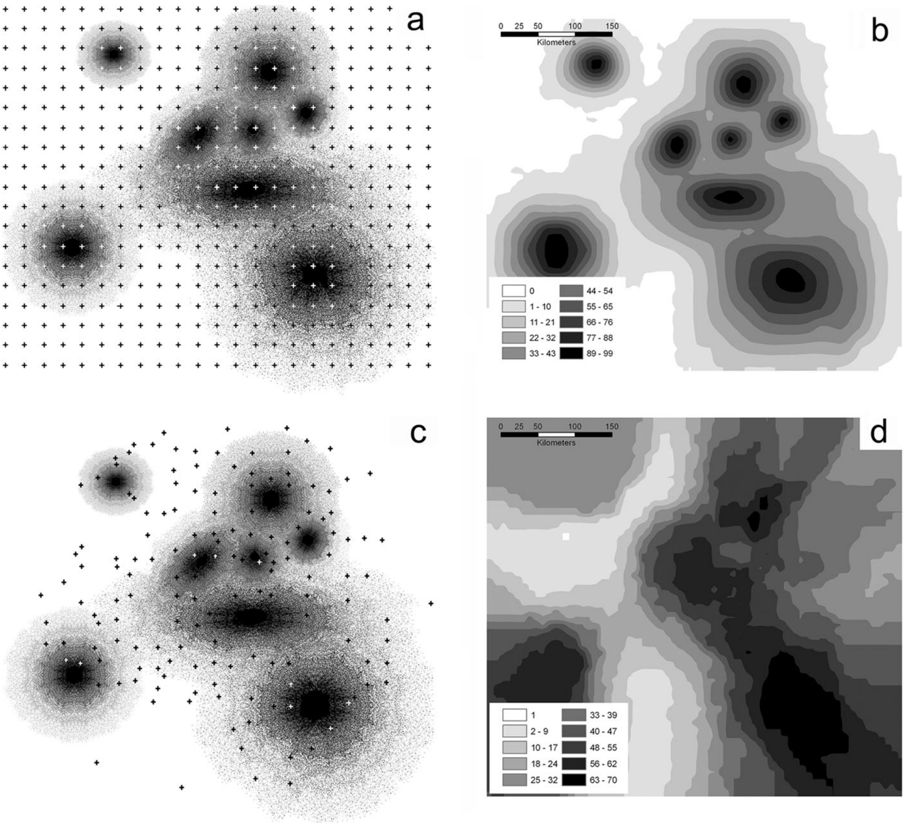

**Fig. 3** The structure of a simulated lithic landscape modeled by means of geostatistic interpolation (kriging); **a** 437 sampling units arranged in a regular grid; **b** spatial model (continuous surface map) constructed with data obtained from **a**; **c** 154 irregularly distributed sampling units; **d** spatial model (continuous surface map) constructed with data obtained from **c**

in error analysis; adjustments for subtle differences in value over short distances in order to smooth plots; control of redundancies in the covariance matrix and of clustering in data points) that make it the better available option under most circumstances.

### *Lithic Landscape Models and Their Value*

A last but key issue to be discussed here concerns the value that the modeling of regional lithic landscapes may have in relation with the degree of existing knowledge about the raw materials represented in sources and lithic assemblages as well as the link we can establish between georeferenced artifacts and specific raw material sources (*i.e.*, sourcing). In any given region, the knowledge about the lithic resource base for each specific toolstone—in terms of kind, quantity, distribution, and geochemical fingerprinting of sources—can be quite diverse: while for some, it can be very high, for others, it may be very low or even nonexistent. In the case of artifact assemblages, the information about intraclass and interclass diversity and variability of the raw materials represented can also be very different in terms of grain and resolution. Finally, the hypothetical linkage established between single isolated artifacts or set of artifacts and specific raw material sources can have different degrees of probability depending on factors such as the nature of the toolstone and the sourcing technology used in each case.

The formal relationships between the different degree of knowledge about the variability of the raw materials represented in both the sources and lithic assemblages and the relative value of the spatial models of lithic landscapes are shown in Fig. 4. Scenario A (− −) depicts a situation where there is scarce information about both the variability of one or many toolstone classes represented in lithic assemblages across the regional space and the size, accessibility, localization, and quality of their likely or actual sources. In this case, the spatial model of the lithic landscape—whose primary value is exploratory rather than conclusive—has the potential to contribute to the formulation of working hypotheses about source localization, thus helping to planning

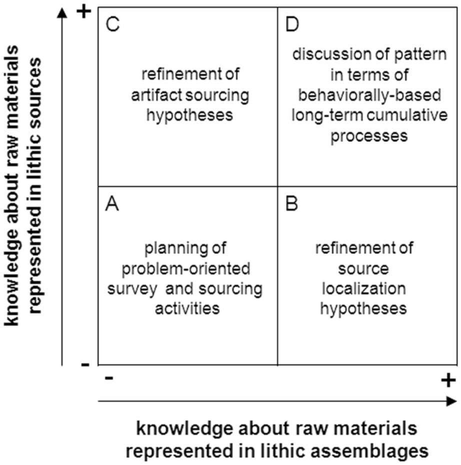

**Fig. 4** Formal relationships between the different degree of knowledge about the raw materials represented in both the sources and lithic assemblages and the relative value of the spatial modeling of lithic landscapes

problem-oriented surveys and sourcing activities. Scenario B (+ −) portrays a case where the entire range of variability of one or many toolstone classes represented in lithic assemblages is well known, but the knowledge about the localization of their likely or actual sources is incomplete. In this case, the model has the potential to contribute to the refinement of source localization hypothesis. Scenario C (− +) typifies the situation in which the knowledge about the characteristics of the regional lithic resource base is good, but the information about the variability of one or many toolstone classes represented in lithic assemblages is incomplete. In this case, the model may help to refine hypotheses about the likely provenience of specific artifacts or set of artifacts. Scenario 4 (+ +), finally, depicts a situation in which the knowledge about both the variability of one or many toolstone classes represented in lithic assemblages and the localization and characterization of their actual sources is high. In this case, the model would be reliable enough to allow the discussion of spatial patterning mainly in terms of behaviorally based, long-term cumulative processes.

Synthesizing, we can say that the spatial modeling of lithic landscapes has a heuristic value in the sense of suggesting ways in which further research may profitably be conducted. Its potential to deal with data of different quality makes it a versatile tool that can be used to integrate information at different stages of the research, allowing for the generation and testing of hypotheses concerning to both source localization and spatial structure of the scatter areas.

## The Explanation of Patterns

### *Coping with Equifinality and Long-Term Processes in the Archaeological Explanation of Patterns*

The wide-scale patterned distribution of lithic artifacts, as revealed by our spatial models, needs to be explained in terms of their generative mechanisms, *i.e.*, those structures, forces, or tendencies operating at the deepest level of reality, which are the intransitive objects of scientific enquiry (Bhaskar 1975). At this point, the question is, what kind of explanation should we prefer? Among the early philosophers of explanation, there was a broad consensus that all explanation is, in principle, a causal one (*e.g.*, Salmon 1984) and that the building of a universal theory of scientific explanation is a desirable, realizable, and legitimate goal (French and Saatsi 2011). Today, a multiplicity of accounts of explanations exists—some of them even adopting a non-causal form (*e.g.*, Nerlich 1979; Sober 1983; *cf.* Skow 2013; Strevens 2008)—partially as a consequence of the increasing awareness among philosophers and scientist alike, that each field of enquiry has its own explanatory goals and styles of knowledge building (French and Saatsi 2011; Woodward 2011). Regarding the explanation of the structural aspects of lithic landscapes, we should choose, among the available alternatives, the one that better fits our needs when trying to cope with an insidious problem in spatial analysis—and in archaeological inference in general (Lyman 2004; Rogers 2000)—that is, equifinality in long-term processes (von Bertalanffy 1950; Driesch 1929).

Two or more processes can be "…called equifinal if they produce outcomes that are […] similar enough that current statistical methods have difficulty distinguishing between them" (Rogers 2000, p. 721). In our context, equifinality is the probability that any single pattern of artifact distribution would be equally caused by different spatial processes (Gibbon 1984, p. 244). Notwithstanding the fact that equifinality is recognized as posing a serious quandary for archaeological explanation, archaeologists in general have yet not addressed the problem with due interest and concern (Lyman 2004, p. 25; for exceptions in lithic studies, see Hodder and Orton 1976, pp. 127–154; Ortega *et al.* 2014, p. 465; Renfrew 1977, pp. 85–86; Shott 2010, pp. 327–328; Stark and Garraty 2010, pp. 40–41).

From a perspective more centered in the interpretation and explanation of the archaeological record rather than in the inferential reconstruction of ancient dynamics (Holdaway *et al.* 2008, p. 111), past processes along with other contemporary factors have, in archaeological inquiry, an explanatory role rather than the role of subject matter (Teltser 1995, p. 3). Within this framework, the approach to the explanation of the patterned distributions of lithic artifacts should be probabilistic (Brantingham 2003, 2006; Ingbar 1994) and plural. This implies that insofar any specific pattern can be generated by a potentially infinite number of mechanistic models (Premo 2010, pp. 31–34; Turchin 2003, p. 18; 2006, p. 454), we must construct many of such models (preferentially of the simulative type, which can be considered as particular applications of the experimental method; Madella *et al.* 2014, p. 252) based on differing assumptions about the underlying dynamic process and then assess how well they fit, individually or in combination, to the available data (for a recent discussion about how mathematical modeling and expert judgment can be combined to achieve credible conclusions, see Weisberg 2010). To put it simply, then, the ideal move in (mostly) data-driven, historical, and correlational sciences like ours is from pattern to process and then again to pattern, in a recursive or iterative way (Amick *et al.* 1989).

Formal modeling and simulation effort about the impact of relevant variables (*e.g.*, those that have been widely explored under the organization of technology model like, among others, mobility, land use patterns, overall levels of planning, and exchange paths; Beck *et al.* 2002; Brantingham 2006; Carr and Bradbury 2011; Close 2000; Charlin 2009; Féblot-Augustins 1993, 1997; Kelly 1988, 1992; Khun 1995, 2004; Nelson 1991; Surovell 2003) on the distributional patterns of artifacts and of their attributes (including raw materials) are yet very scarce and mostly focused on the short- or medium-term consequences of such variables (*e.g.*, Brantingham 2003, 2006; Cole 2005; Grove 2010; Hodder 1978; Hodder and Orton 1976; Ingbar 1994). It cannot be overemphasized that more research on these topics is urgently needed in order to provide the basis for a probabilistic explanation of archaeological distributions, particularly in terms of the differential contribution of relevant factors and processes. However, it is important to take into account that most of the available models are framed into a synchronic and functional approach (Wandsnider 2003), in which processes are scoped at the short to medium term (ecological time). Any useful model has to incorporate a longer temporal perspective to fit the reality of the lithic component of the archaeological record, whose material and relational elements accumulate and change—as a consequence of postdepositional factors (Doelman 2008)—in evolutionary time.

### *In Search of an Appropriate Form of Explanation*

Due to the insidious nature of equifinality, we think that a proper approach to the explanation of the empirically grounded inferences about the structure of lithic landscapes would be that proposed by Sober (1983), named the equilibrium explanation (EQ). This is an allegedly noncausal form of explanation (for a different interpretation, see Skow 2013; Strevens 2008) in which "…an outcome is explained by showing that a very large number of initial states of a system will evolve in such a way that the system ends up in the outcome state that we wish to explain, but in which no attempt is made to trace the actual sequence of events leading up to that outcome" (Woodward 2011). In fact, EQ is based on the assumption that to explain a given state of affairs, the identity of the "actual" cause does not really matter "as long as it is one of a set of possibilities of a certain kind" (Sober 1983, p. 140). To know what the actual cause of an event is—in the common view, the very objective of scientific research—we have to be able to say which of a set of alternative answers is correct. If those alternatives are not easy to pry apart, knowing what the cause is may be difficult or even impossible to achieve (Sober 1983, p. 141). This is precisely the context in which EQ finds its relevance.

Equilibrium explanation is an account of explanation particularly useful for historical sciences like paleontology, geology, and archaeology to the extent that they deal with the effects—as they are seen from the present—of long past causes, particularly of causes whose necessity for the attributed effects is unknown. In contexts where equifinality is an issue, EQ appears as an adequate form of explanation that deserves further exploration in our field.

Summing up, the formulation of well-defined explanatory hypothesis about well-described patterns, the development of many simulative models designed to both, assessing the efficacy of different causal factors and processes and measuring the degree of overlapping of their effects, would constitute an adequate approach to cope with the problem of equifinality in the explanation of spatial patterning in the archaeological record.

## Descriptive/Interpretive Modeling of Lithic Landscapes: a Case Study

The aim of this section is to introduce the application of the proposed methodology for the descriptive and interpretive modeling of lithic landscapes. We chose as an example a study case with which we are familiar, the Late Holocene lithic record of east-central Argentina, examining the spatial variation in relative frequency of three broadly defined classes of toolstone represented in lithic artifact assemblages (for a quite similar methodological approach, see Biró 1998; Biró and Regenye 1991). On the basis of the spatial models generated for each toolstone class, we address two main issues: (1) the relationship between, on one hand, the type and location of the sources and, on the other, the size and shape of the respective scatter areas; and (2) the reciprocal relationships between different raw material sources. It is expected that, beyond the specifics of the case, this example illustrates well both the problems and possibilities of the advocated approach.

### The Study Area

The portion of the Argentine territory that we call east-central Argentina (35.5° -41.5° S; 56.5°-67.5° W; ≈480,000 km$^2$) includes a significant section of the Pampas and the northeast of Patagonia (Fig. 5). The Pampas, a grassland/steppe biome inhabited by hunter-gatherers from the late Pleistocene to historical times, comprise a flat to slightly undulating surface landscape, which is alternatively underlain by deep layers of loess, loessoids, and sand. The Pampas are subdivided into two major environments: an eastern zone characterized by humid temperate prairies (Humid Pampas) and a western zone typified by dry steppes of moderate continental climate (Dry Pampas). This vast and continuous plain is interrupted by two major orographic systems, Tandilia and Ventania, smaller hilly ranges (*e.g.*, Lihué-Calel, Choique-Mahuida, Calencó), as well as by a number of isolated hills (*e.g.*, Cerro Cortapié), and scattered rocky outcrops (*e.g.*, Cuchillo Có, Lumb). Northeastern Patagonia is a semiarid region located south of the Colorado River. It comprises the lower valleys of the Colorado and Negro rivers, the intermediate plateau, and the coastal area. In this region, rocky outcrops are scarce and isolated (*e.g.*, Cerro El Puntudo), being the most relevant geologic feature the Patagonian Shingle Formation (Tehuelche Beds or Rodados Patagónicos), composed of gravel deposits of extraregional provenance (Fidalgo and Riggi 1965, 1970; Martínez *et al.* 2009).

In east-central Argentina, there were two main kinds of raw materials used by prehistoric hunter-gatherers for tool-making: quartzites (orthoquartzites and methaquartzites) and cryptocrystalline quartz (*e.g.*, chalcedonies and opaque siliceous rocks like jaspers, cherts, and silicified dolomite) (Andreis and Torres Ribeiro 2003; Dalla Salda *et al.* 2006; Harrington 1947). Other rocks like basalts, rhyolites, limestones, silicified tuffs, granites, or sandstones were also available (Harrington 1947; Linares *et al.* 1980), but they seem to have been of second order importance for subsistence activities. Despite the growing interest over the past three decades in the systematic and detailed study of lithic assemblages and in the detection of potential and factual sources of toolstone, very little of the lithic materials recovered in

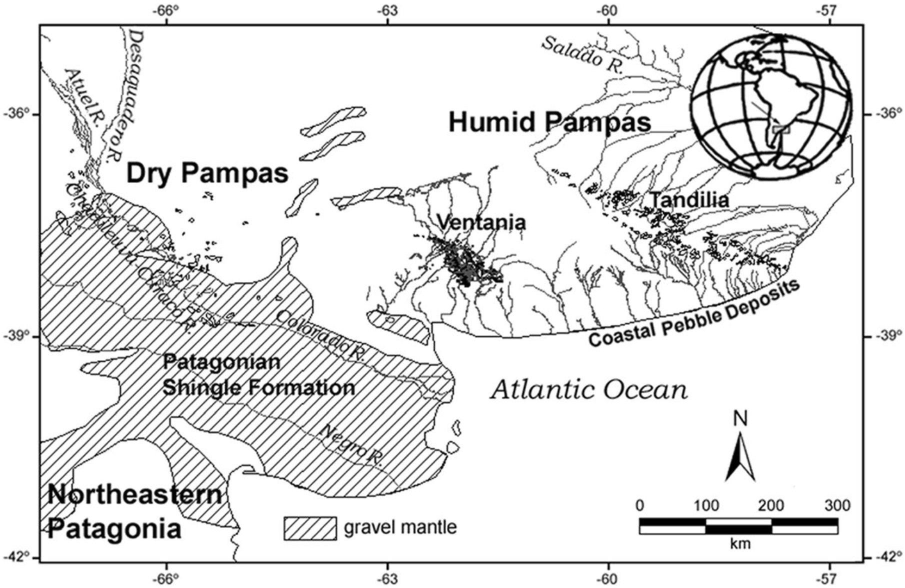

**Fig. 5** Map of east-central Argentina showing the main orographic features and toolstone sources

archaeological sites have been rigorously sourced using methods other than visual assessment of hand specimens. Among the few sourcing studies that used petrographic techniques (XRD and/or thin-section microscopy) carried out in our study area, we can mention those of Barros (2009), Barros and Messineo (2004), Bayón *et al.* (1999), Berón (2006), Catella (2014), Catella *et al.* (2010), Flegenheimer *et al.* (2003), Matarrese and Poiré (2009), Messineo *et al.* (2004), and Valverde (2002).

The sources of opaque siliceous rocks or ORS (*e.g.*, cherts and jaspers) are very diffuse, in the sense of being extensive and difficult to delimit. These rocks appear, in relatively low proportions, intermixed with Andean igneous and metamorphic rocks (predominant), as well as other stones (*e.g.*, chalcedonies, quartzites, quartz, silicified tuff, wood opal) within the extended gravel mantles of extraregional provenance that compose the Patagonian Shingle Formation (Martínez *et al.* 2009). Secondary sources of these toolstones are some derived formations, like the river gravel deposits associated with paleochannels of the Colorado River and the coastal pebble deposits of the Humid Pampas (the latter resulting from a complex process in which pebbles from the Patagonian Shingle Formation are transported to the sea by river streams, dispersed northward across the continental shelf by littoral currents, and then deposited on the Pampean beaches by storms and tides; Ameghino 1909; Frenguelli 1931) (Armentano 2004; Barros 2009; Berón 2006; Bonomo 2005; Bonomo and Prates 2014; Catella 2014; Fidalgo and Riggi 1965, 1970). Quartzites are abundant in Tandilia and Ventania, although there are smaller outcrops scattered over the plains of the Humid and Dry Pampas (Andreis and Torres Ribeiro 2003; Berón 2006; Charlin 2002; Flegenheimer and Bayón 2002; Kostadinoff 2007; Linares *et al.* 1980). From a geological standpoint, quartzites are present in at least 15 lithologic units in this region, most of them cropping out in Ventania and Tandilia (Dalla Salda *et al.* 2006; Harrington 1947; Linares *et al.* 1980). They present very different qualities for flintknapping and their sources, which have a different degree of availability, accessibility, and exploitability, are heterogeneously distributed across the landscape (Bayón *et al.* 1999; Catella 2014; Catella *et al.* 2010). However, the primary and secondary sources of high-quality raw materials—mostly orthoquartzites—are extremely scarce and localized (*i.e.*, point sources) (Catella 2014; Catella *et al.* 2013; Colombo 2011, 2013).

The sources of chalcedonies, finally, are much less conspicuous than those of quartzites, but they are also highly localized, particularly the primary ones (Barros and Messineo 2004; Berón 2006; Cardillo and Scartascini 2007). The main diffuse sources of chalcedonies are the primary and secondary deposit of the Patagonian Shingle Formation (Berón 2006; Carrera Aizpitarte 2010).

Most of the secondary deposits of toolstones are of natural origin, but there are lines of evidence that, in some areas at least, the implementation by prehistoric hunter-gatherer of different provisioning strategies (Khun 1995, 2004), particularly at the level of places—*i.e.*, through the formation of caches (Oliva and Perez 2008) or the transport and local accumulation of nodules or cores (Martínez 1999)—led to the lithification (*sensu* Webb 1993) of otherwise lithic-free landscapes (Martínez and Mackie 2003). Because only a very small fraction of the assemblages recovered at different archaeological sites have been rigorously sourced, it is relevant to check if the spatial variation in the proportion of each main toolstone class exhibits a coherent geographic pattern, in terms of frequency peaks and fall-off curves, particularly in relation with their factual and potential sources.

## Materials and Methods

In order to construct an exploratory model of the lithic landscape of east-central Argentina, we carried out an extensive survey of the relevant literature, searching for suitable quantitative data about the composition of lithic assemblages recovered from site components of Late Holocene age (ca. 3000–200 $^{14}$C years BP). This time period, during which a number of significant processes seem to have been occurred (*e.g.*, demographic increase, effective occupation of the entire territory, economic intensification, higher levels of interconnection across regional boundaries; Barrientos 1997; Bayón and Flegenheimer 2004; Berón 2004, 2007; González de Bonaveri *et al.* 1999; Martínez 1999, 2008–2009; Politis and Madrid 2001), is well represented archaeologically in the whole region. As a result, we collected a preliminary sample of around 150 georeferenced lithic assemblages. On the basis of the information provided by the corresponding reports, we calculated the relative frequency (*i.e.*, percentages) of the toolstone classes represented in each assemblage. We choose percentages because they are useful for comparing information where the sample sizes or totals are very dissimilar and because they are a kind of data that is widely available in the literature. Any collection with less than 25 artifacts was excluded from the database since sample sizes below that minimum complicate the estimation of the relative frequencies.

To avoid the overcrowding of data from intensively surveyed areas in the landscape, we aggregated into composites the information from sites separated each other by a linear distance less than 1 km (*i.e.*, an archaeological locality). It is deemed unproblematic, at the spatial scale in which the study was framed, the creation of composite assemblages by integrating data from very close sites whose boundaries, on the other hand, are generally not well specified in the literature. The aggregation of data has the advantage of avoiding the overcrowding of points, which is a problem in spatial analysis, while allowing retaining information from individual sites that, because of its small sample size, would be otherwise excluded from the analysis. The negative impact of this procedure on the overall picture can be considered negligible, taking into account the scale of our level of analysis, the rather small number of cases (20/119; 16.8 %), the particularities of the interpolation technique used to generate the spatial models, and the exploratory aim of this study. Data from the screened database ($n$=119; Table 1, Fig. 6) were, finally, entered into a spreadsheet for further analysis with the statistics software PAST 2.17 and the GIS package ArcGIS 9.3.

For the sake of simplicity, we chose to analyze the spatial distribution of artifacts made with raw materials belonging to just three groups of rocks, namely quartzites, chalcedonies, and OSR. These toolstones are those with the highest level of representation in the archaeological assemblages and those whose main sources are relatively known, albeit in a generic rather than a specific way. Although recent studies carried out in the study area have shown that these broad classes of rocks are composed by a variety of subtypes, like metaquartzites, orthoquartzites, and quartz sandstones in the case of quartzites (Bayón *et al.* 1999; Catella 2014; Catella *et al.* 2010, 2013), and different kinds of cherts, jaspers, and other silicified stones in the case of OSR (Armentano 2004, Martinez *et al.* 2009), in this paper, we decided to use broad categories for two reasons: (i) because the relevant information to establish a greater discrimination is not present in most of the reports used to generate the regional database and (ii) because the relative underdevelopment of intensive sourcing research in the area.

**Table 1** Archaeological sample from east-central Argentina utilized to model lithic landscapes

| No. | Site/locality | Sample Size | % OSR | % Qtzt | % Cha | References |
|---|---|---|---|---|---|---|
| 1 | Agua del Fresco | 39 | 38.46 | 0.00 | 0.00 | Berón (2004) |
| 2 | Angostura 1 | 998 | 45.29 | 0.10 | 7.62 | Prates (2008) |
| 3 | Arenas Verdes | 95 | 3.20[a] | 66.40 | 9.50 | Bonomo (2005) |
| 4 | Arroyo Saudade 1 | 109 | 0.00 | 100.00 | 0.00 | Catella *et al.* (2013) |
| 5 | Arroyo Seco 2 | 143 | 2.80 | 60.84 | 4.90 | Leipus (2006) |
| 6 | Badal | 194 | 3.60 | 0.00 | 84.53 | Austral (1971) |
| 7 | Blanca Grande | 364 | 6.04 | 60.71 | 30.49 | Bórmida (1960) |
| 8 | Cabeza de Buey | 165 | 2.42 | 64.24 | 33.33 | Bórmida (1960) |
| 9 | Caldén Guazú M1SE | 426 | 52.00 | 2.64 | 14.39 | Armentano (2004) |
| 10 | Calera Avellaneda | 5,258 | 1.00 | 25.90 | 69.68 | Barros and Messineo (2007) |
| 11 | Campo Brochetto | 91 | 0.00 | 32.80 | 62.60 | Barrientos and Leipus (1997) |
| 12 | Cantera Barker | s/d | 0.00[b] | 98.00[b] | 2.00[b] | Flegenheimer *et al.* (1996) |
| 13 | Cantera La Liebre | 1,153 | 0.00 | 7.00 | 0.00 | Flegenheimer (1991) |
| 14 | Caracolero | 102 | 2.90 | 11.70 | 5.90 | Madrid *et al.* (2002) |
| 15 | Cerro Aguirre | 663 | 0.00 | 0.00 | 100.00 | Lozano (1991) |
| 16 | Cerro Casa de Piedra 1 | 278 | 37.65 | 0.00 | 0.00 | Gradín (1984) |
| 17 | Cerro Cortado COMP | 29 | 65.52 | 0.00 | 0.00 | Berón (2004) |
| 18 | Cerro La China COMP | 480 | 0.00 | 94.18 | 2.83 | Mazzia and Flegenheimer (2007) |
| 19 | Cerro Núcleo Central-1 | 558 | 0.00 | 10.03 | 89.61 | Barros and Messineo (2004) |
| 20 | Cerro Tres Lomas 1 | 8,372 | 0.00 | 3.58 | 4.12 | Messineo *et al.* (2009) |
| 21 | Chenque 1-La Casona COMP | 1,376 | 57.85 | 1.89 | 0.00 | Berón (2004) |
| 22 | Claromecó 1 | 423 | 7.32 | 2.00 | 1.60 | Bonomo *et al.* (2008) |
| 23 | Confluencia 1 and 2 COMP | 250 | 44.80 | 0.80 | 0.00 | Berón (2004) |
| 24 | Costa Bonita COMP | 1,115 | 32.64 | 5.56 | 0.26 | Loponte (1987) |
| 25 | Cueva del Tigre | 156 | 2.60 | 58.30 | 22.50 | Madrid *et al.* (2002) |
| 26 | Cueva Tixi | 1,304 | 0.31 | 97.08 | 0.15 | Mazzanti (1997) |
| 27 | Dique Lara COMP | 404 | 28.71 | 0.00 | 17.33 | Berón (2004) |
| 28 | Don Aldo 1 | 130 | 24.60 | 0.00 | 16.90 | Prates (2008) |
| 29 | El Caldén | 2,136 | 19.19 | 2.80 | 26.96 | Armentano (2010) |
| 30 | El Carancho | 72 | 0.00 | 0.00 | 0.00 | Berón (2004) |
| 31 | El Castillo | 138 | 63.76 | 0.00 | 0.00 | Berón (2004) |
| 32 | El Cruce | 35 | 51.42 | 0.00 | 0.00 | Berón (2004) |
| 33 | El Encuentro | 137 | 32.84 | 0.00 | 0.00 | Berón (2004) |
| 34 | El Guanaco 1 | 750 | 1.60 | 70.53 | 4.13 | Bayón *et al.* (2006) |
| 35 | El Molino | 40 | 52.50 | 0.00 | 0.00 | Berón (2004) |
| 36 | El Palomar 1 and 2 COMP | 292 | 18.49 | 65.41 | 0.34 | Austral (1965) |
| 37 | El Puente | 919 | 0.00 | 33.62 | 53.32 | Kaufmann and Messineo (2010) |
| 38 | El Puma 1, 3, and 4 COMP | 4,564 | 20.95 | 1.60 | 15.95 | Martínez *et al.* (2012) |
| 39 | El Remanso Grande | 152 | 64.47 | 0.66 | 0.00 | Berón (2004). Curtoni (1999) |
| 40 | El Tigre HCSN | 219 | 45.12 | 0.47 | 44.65 | Armentano (2004) |

**Table 1** (continued)

| No. | Site/locality | Sample Size | % OSR | % Qtzt | % Cha | References |
|---|---|---|---|---|---|---|
| 41 | Escuela Agropecuaria | 1,962 | 0.15 | 58.46 | 39.44 | Crivelli Montero *et al.* (1994) |
| 42 | Faro Guaraní 1 | 122 | 1.60 | 0.80 | 0.80 | Bonomo (2005) |
| 43 | Farola de Monte Hermoso | 207 | 0.00 | 90.82 | 0.48 | Bayón and Zavala (1994) |
| 44 | Flor del Pago | 53 | 88.68 | 0.00 | 0.00 | Berón (2004) |
| 45 | Fortín Necochea 1 | 3,098 | 0.00 | 68.84 | 29.24 | Crivelli Montero *et al.* (1994) |
| 46 | Gascón 1 | 139 | 1.48 | 32.59 | 19.25 | Oliva *et al.* (2007) |
| 47 | Jagüel | 9,138 | 6.00 | 68.00 | 15.00 | Saghessi and Petz (2007) |
| 48 | La Colorada 1 to 6 COMP | 577 | 0.00 | 92.55 | 7.45 | Aldazabal and Cáceres (1999) |
| 49 | La Estafeta 1 | 428 | 1.40 | 77.10 | 14.30 | Bonomo (2005) |
| 50 | La Isla | 920 | 0.43 | 85.32 | 0.65 | Bayón *et al.* (2006) |
| 51 | La Montaña | 652 | 3.53 | 40.00 | 6.75 | Catella (2014), Oliva (2014) |
| 52 | La Primavera | 179 | 43.57 | 10.71 | 8.57 | Armentano (2004) |
| 53 | La Raquel 2 | 1,678 | 4.00 | 49.47 | 37.41 | Eugenio *et al.* (2007) |
| 54 | La Soberana | 30 | 2.56 | 56.41 | 2.56 | Bayón *et al.* (2006) |
| 55 | La Sofía COMP | 55 | 1.82 | 81.82 | 1.82 | Catella (2014), Oliva (2014) |
| 56 | La Terracita-La Lomita COMP | 75 | 61.33 | 0.00 | 0.00 | Berón (2004), Curtoni (1999) |
| 57 | La Toma | 95 | 0.00 | 63.00 | 30.00 | Madrid and Politis (1991) |
| 58 | Laguna Blanca Chica | 923 | 0.88 | 43.23 | 55.58 | Barros and Messineo (2004), Messineo and D'Augerot (2004) |
| 59 | Laguna Chasicó 1, 5, 6, and HA COMP | 464 | 9.27 | 38.36 | 3.88 | Catella (2014) |
| 60 | Laguna Chasicó 2 and 3 COMP | 429 | 35.43 | 25.41 | 7.69 | Catella (2014) |
| 61 | Laguna Chasicó 4 | 30 | 3.33 | 26.67 | 23.33 | Catella (2014) |
| 62 | Laguna Chasicó 7 | 187 | 14.43 | 56.68 | 6.41 | Catella (2014) |
| 63 | Laguna Chasicó 8 | 221 | 2.26 | 81.44 | 2.71 | Catella (2014) |
| 64 | Laguna Chillhué 1, 2, and 3 COMP | 279 | 54.48 | 26.52 | 0.00 | Berón *et al.* (2002–2004) |
| 65 | Laguna Cubiló | 142 | 4.23 | 51.41 | 38.03 | Bórmida (n/d, 1960) |
| 66 | Laguna de Chapalcó | 49 | 8.16 | 4.08 | 6.12 | Carrera Aizpitarte (2007) |
| 67 | Laguna de Puán 1 | 112 | 0.00 | 80.00 | 8.00 | Oliva *et al.* (1991) |
| 68 | Laguna de Rojo | 27 | 3.70 | 40.74 | 18.52 | Carrera Aizpitarte (2007) |
| 69 | Laguna de Sotelo | 172 | 0.58 | 70.35 | 18.60 | Eugenio and Aldazabal (1987–1988) |
| 70 | Laguna del Trompa | 861 | 0.50 | 73.87 | 24.16 | Crivelli Montero *et al.* (1994) |
| 71 | Laguna el Recado | 81 | 9.88 | 55.56 | 33.33 | Bórmida (1960) |
| 72 | Laguna La Barrancosa 1 | 4,339 | 3.34 | 91.22 | 1.96 | Pal (2007) |
| 73 | Laguna La Barrancosa 2 | 929 | 1.00 | 25.94 | 68.35 | Barros and Messineo (2004) |
| 74 | Laguna La Dulce | 154 | 24.67 | 0.00 | 0.00 | Berón (2004) |
| 75 | Laguna La Larga | 403 | 0.70 | 64.30 | 23.80 | Madrid *et al.* (2002) |

**Table 1** (continued)

| No. | Site/locality | Sample Size | % OSR | % Qtzt | % Cha | References |
|---|---|---|---|---|---|---|
| 76 | Laguna La Leona | 33 | 63.63 | 0.00 | 0.00 | Berón (2004) |
| 77 | Laguna Las Tunas Grande | 1,083 | 0.66 | 33.00 | 61.00 | Gavilán *et al.* (2004) |
| 78 | Laguna Los Chilenos 2 | 463 | 2.59 | 76.46 | 6.91 | Catella (2014), Oliva (2014) |
| 79 | Laguna Ovalla | 107 | 0.90 | 66.40 | 16.90 | Madrid *et al.* (2002) |
| 80 | Laguna Pincén | 669 | 0.00 | 27.00 | 4.00 | Moirano (1999) |
| 81 | Laguna Traru Lauquen | 47 | 0.00 | 0.00 | 0.00 | Berón (2004) |
| 82 | Laguna Tres Reyes 1 | 77 | 3.35 | 71.18 | 13.48 | Madrid *et al.* (1991) |
| 83 | Las Brusquillas 1 | 1,105 | 2.90 | 70.60 | 20.60 | Massigoge and Pal (2011) |
| 84 | Las Cortaderas 1 | 253 | 0.00 | 85.80 | 13.40 | Massigoge (2007) |
| 85 | Localidad Parque Luro COMP | 2,091 | 19.08 | 9.80 | 11.86 | Carrera Aizpitarte (2007) |
| 86 | Localidad Tapera Moreira COMP | 669 | 51.87 | 1.20 | 0.00 | Berón (2004), Curtoni (1999) |
| 87 | Loma de los Muertos | 207 | 35.00 | 1.45 | 10.00 | Prates *et al.* (2010) |
| 88 | Loma Ruiz 1 | 268 | 20.40 | 18.90 | 16.60 | Martínez (2004) |
| 89 | Los Sandovales | 31 | 90.32 | 0.00 | 0.00 | Berón (2004) |
| 90 | Mar del Sur | 226 | 6.60 | 3.50 | 4.00 | Bonomo (2005) |
| 91 | Médano Blanco | 94 | 0.00 | 97.87 | 0.00 | Bayón and Zavala (1994) |
| 92 | Médano Santa Clara | 347 | 0.00 | 19.30 | 43.51 | Madrazo (1972) |
| 93 | Médanos Colorados | 447 | 0.00 | 1.10 | 75.33 | Austral (1975) |
| 94 | Médanos de Villa | 66 | 68.18 | 0.00 | 0.00 | Berón (2004) |
| 95 | Médanos del 18 COMP | 544 | 36.21 | 0.18 | 0.00 | Berón (2004) |
| 96 | Médanos del 24 | 162 | 41.98 | 0.00 | 0.00 | Berón (2004) |
| 97 | Médanos del Fondo | 25 | 56.00 | 0.00 | 0.00 | Berón (2004) |
| 98 | Memoria del Fresco | 746 | 8.17 | 0.00 | 0.00 | Berón (2004) |
| 99 | Moromar | 295 | 9.80 | 2.00 | 0.70 | Bonomo (2005) |
| 100 | Negro Muerto | 981 | 59.79 | 0.10 | 13.64 | Prates (2008) |
| 101 | Nutria Mansa 1 | 1,603 | 1.70 | 82.10 | 5.00 | Bonomo (2005) |
| 102 | Paso Mayor 1 and 2 COMP | 173 | 0.58 | 91.91 | 0.58 | Austral (1967–1968), Bayón *et al.* (2006) |
| 103 | Ponciano Anquito | 154 | 66.88 | 3.25 | 0.00 | Berón (2004), Curtoni (1999) |
| 104 | Puesto Córdoba | 30 | 30.00 | 3.33 | 0.00 | Berón (2004), Curtoni (1999) |
| 105 | Puesto Patiño | 58 | 36.21 | 0.00 | 0.00 | Berón (2004) |
| 106 | Quequén Salado 1 | 4,559 | 9.50 | 36.80 | 17.80 | Bonomo (2005) |
| 107 | Quequén Salado 3 and 4 COMP | 67 | 2.98 | 80.59 | 11.94 | Madrid *et al.* (2002) |
| 108 | Rincón del Álamo | 26 | 42.30 | 0.00 | 0.00 | Berón (2004) |
| 109 | Salinas Chicas | 29 | 24.14 | 13.79 | 10.34 | Catella (2014) |
| 110 | San Antonio | 560 | 55.18 | 1.43 | 27.86 | Martínez *et al.* (2010) |
| 111 | San Blas COMP | 4,588 | 28.47 | 0.07 | 0.02 | Eugenio and Aldazábal (2004), Outes (1907) |
| 112 | San Luis | 217 | 0.90 | 80.60 | 13.40 | Massigoge (2007) |

**Table 1** (continued)

| No. | Site/locality | Sample Size | % OSR | % Qtzt | % Cha | References |
|---|---|---|---|---|---|---|
| 113 | San Martín 1 | 498 | 3.22 | 79.72 | 4.02 | Catella *et al.* (2010) |
| 114 | Tapera Vieja de Juárez | 225 | 49.33 | 0.00 | 0.00 | Berón (2004) |
| 115 | Vallejo | 26 | 0.00[c] | 2.70[c] | 45.94[c] | Austral (1971) |
| 116 | Villa Iris | 384 | 12.50 | 22.91 | 13.54 | Oliva *et al.* (2006) |
| 117 | Voladero Tulli | 233 | 41.70 | 4.04 | 13.00 | Armentano (2004) |
| 118 | Ybarra | 186 | 0.00 | 75.00 | 10.00 | Moirano (1999) |
| 119 | Zanjón Seco 2 | 1,007 | 0.16 | 96.60 | 1.86 | Politis *et al.* (2004) |

*OSR* opaque siliceous rocks, *Qtzt* quartzites, *Cha* chalcedonies

[a] In the absence of a specific value given in the original report, % OSR was calculated considering that these toolstones represent approximately 8 % of the raw materials of "coastal origin," a category that includes OSR, andesites, rhyolites, basalts, and other rocks (Bonomo 2003, pp. 131–132)

[b] Percentages estimated on the basis of the descriptive account of site findings

[c] Percentages calculated considering only the tool assemblage

Our records fall into the category "sparsely sampled data" (Dixon 2002), since only a subset of all possible event locations has been observed and recorded by the authors of the reports (*i.e.*, preferential sampling). The first step in our analysis was to assess the spatial distribution of sample locations—considered as marked point process data (Stoyan and Stoyan 1994)—by means of a nearest neighbor analysis. The results of the test (convex hull area, Donnelly edge effect correction; nearest neighbor ratio

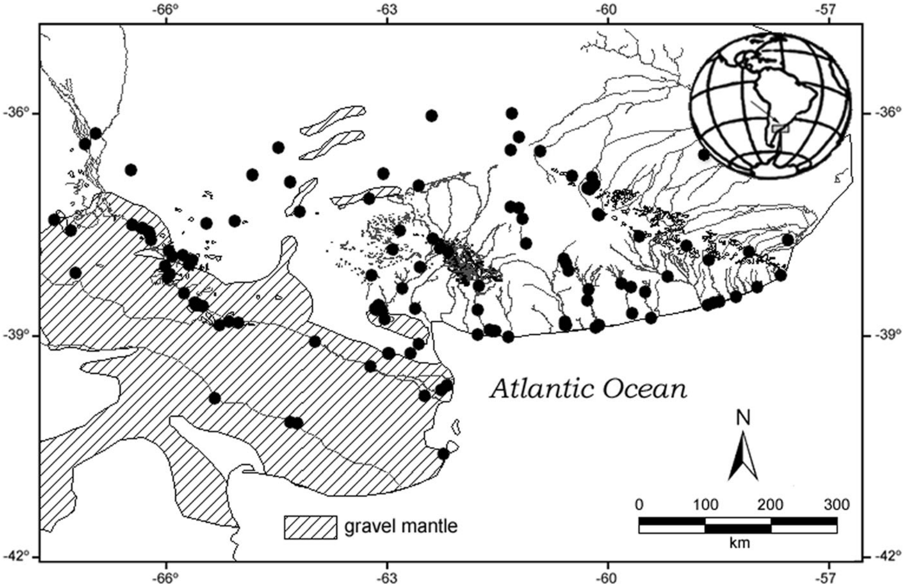

**Fig. 6** Spatial distribution of the sampling units (archaeological sites and localities) used as data source for the construction of spatial models of the lithic landscapes from east-central Argentina

$R = 0.7917$; $z$ score $= -4.0425$; $p$ value $< 0.001$) indicate that the point pattern is clustered, making necessary the implementation of a declustering procedure to adjust for preferential sampling (cell method; Journel 1983). Following a common practice to choose the cell size for declustering, we first proceeded—after performing a normal score transformation of original values—to compute the global mean percentage for a range of cell sizes and then to select the cell size that returned the lowest global mean ($\mu$) (Contaminated Sites Statistical Applications Guidance 2001, p. 2). The second step was to test for trends and anisotropies in data distributions. The third step was to examine the spatial dependence of data using different semivariogram models. At this step, data were analyzed with and without correction for trends or anisotropy. The comparison between the performance of different geostatistical models, considering both the variography and the cross-validation statistics, indicates that the best overall results were obtained with the use of the K-Bessel or Matérn model (detrended data, corrected for anisotropy). It is a model that tends to produce surfaces that are smoother locally (*i.e.*, on a very fine scale) than those generated by other models (Pardo-Iguzquiza and Chica-Olmo 2008). The fourth step was the generation of prediction maps and prediction standard error maps for each of the three toolstone classes by means of simple kriging (different semivariogram models), using for the interpolation between 7 and 10 neighbors within each quadrant of the map. Both map classes were exported to a raster format for further examination and processing.

It is important to note here that spatial models based on relative frequency data contain information not only about the rock class represented in each map but also about the relationships between it and all the other rock classes—and their respective sources—defined in a region (Ingbar 1994). In fact, at each point in the space, any one toolstone can be present at a relative frequency ($f$) with a probability ($p$) that is not a simple function of distance from the source but a function of distance from source, plus a number of intrinsic and extrinsic properties of the rock itself (*e.g.*, mineral composition, internal structure, degree of metamorphism, hardness, fracture) and those of its source (*e.g.*, size, visibility, exploitability) in relation with those of the other available rocks and sources. Therefore, the shape of the fall-off curve obtained from relative frequency data can significantly differ from that derived from other measures like absolute frequency, density, or weight (see examples in Bevan 2012). This makes relative frequency data and derived models particularly indicative about the kind of reciprocal relationship between different regionally available raw materials and sources (Biró and Regenye 1991; Fulford and Hodder 1974; Hodder and Orton 1976; Soja 1971).

Summarizing, in this exploratory study, the unit of analysis is the lithic landscape, which is modeled separately for each toolstone class. The level of analysis is the macroregion (the Pampas and northeastern Patagonia), and the unit of observation is the site or locality.

## Results and Discussion

Figures 7, 8, and 9 represent the 2D models of the lithic landscapes corresponding to each of the three toolstone classes considered (simple kriging, K-Bessel semivariogram; for a summary of the error statistics associated with these models,

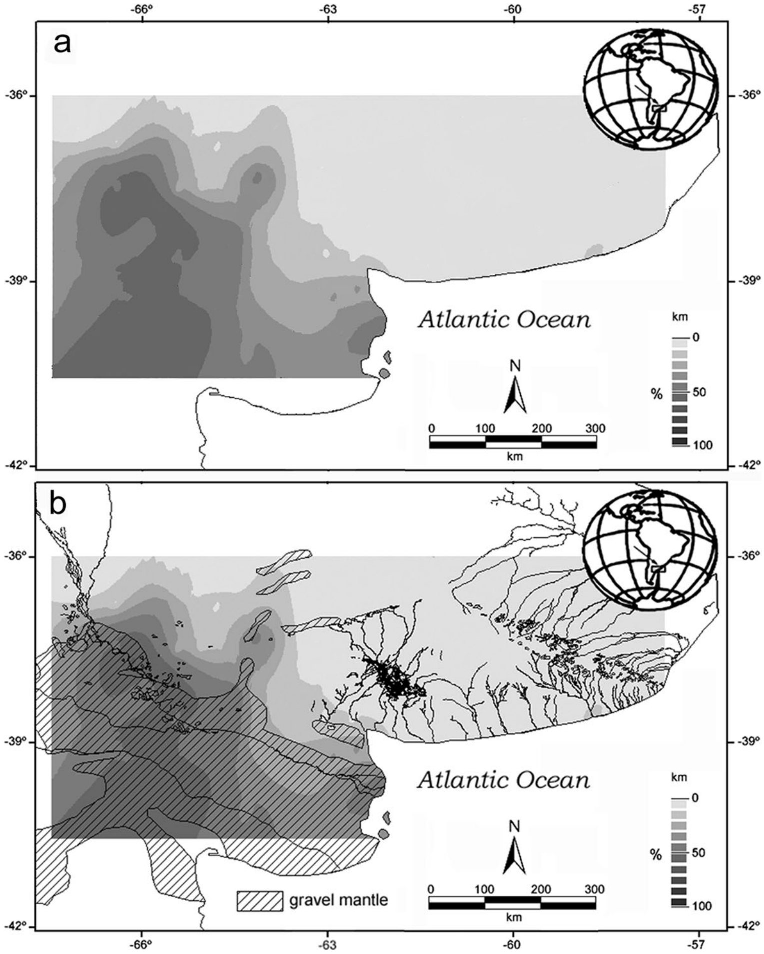

**Fig. 7** Continuous spatial model (raster map) of the lithic landscape of opaque siliceous rocks (OSR) from east-central Argentina (relative frequency data); **a** without physiographic information; **b** with sources, water courses, and water bodies

see Table 2). As it is shown in Fig. 7, OSR have a spatial distribution of percentage values that is highly congruent with the distribution of the Patagonian Shingle Formation and of the pebble deposits found along the coast of the Humid Pampas. The highest percentage values of these rocks (50–70 %) are found around the middle valleys of the Negro and Colorado rivers and along most of the Chadileuvú-Curacó river valley, which are zones that are either well inside the major regional mantle of the Patagonian Shingle Formation or slightly displaced with respect to its northern edge. Lesser peaks (30–40 %) occur in the lower valley and delta of the Colorado River and in relation with minor and isolated deposits of Rodados Patagónicos, which are usually composed of pebbles of smaller size with respect to those from the major, western sources (Witte 1916). Quartzites are mainly concentrated (50+%) around and between the hills of Tandilia and Ventania (Fig. 8), where the main primary sources of quartzites crop out. However, in and around both hilly ranges, the highest peaks of these raw

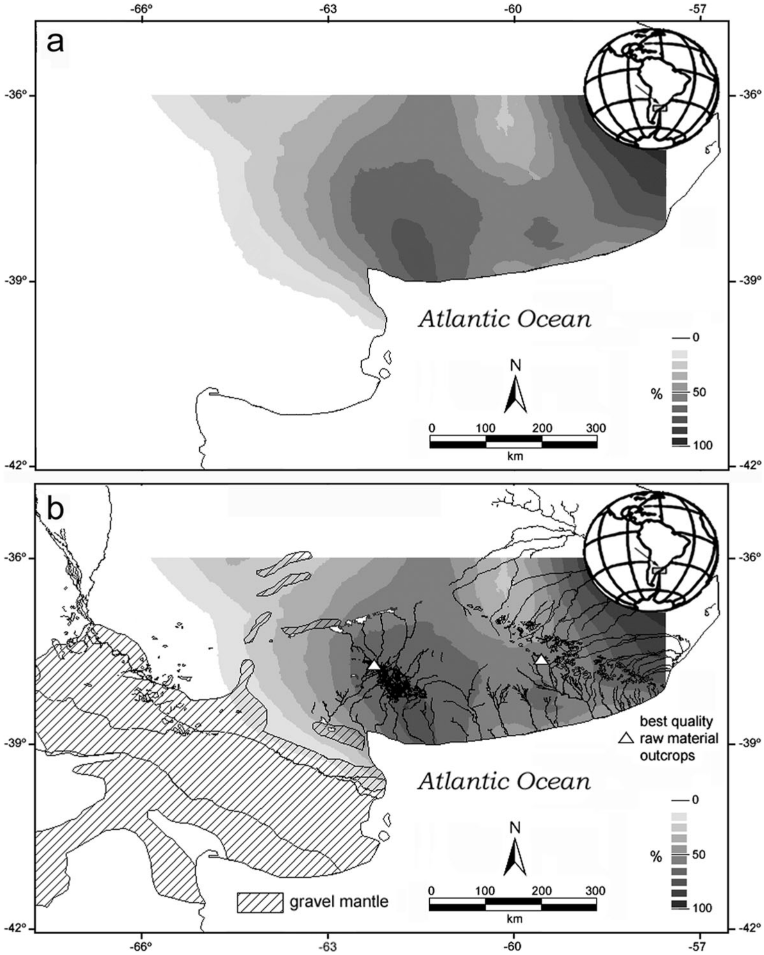

**Fig. 8** Continuous spatial model (raster map) of the lithic landscape of quartzites from east-central Argentina (relative frequency data); **a** without physiographic information; **b** with sources, water courses, and water bodies

materials (70–80 %) do not appear to be preferentially associated with any particular type of source (*i.e.*, primary or secondary sources). Chalcedonies (Fig. 9), in turn, are the most ubiquitous toolstones at the regional level, with at least four peaks of relative frequency distributed in different sectors of space. However, in just one case, coincidence between a frequency peak and a known source was found, which suggests that chalcedony sources—some of them likely not discovered so far—are present in diverse points of the landscape. This is particularly evident in the northern side of the study area, where there are more percentage peaks (50+%) than identified sources. By contrast, in the south and the western sector of the area, there are at least two documented sources that seem to have been exploited at a very local level. The primary sources of OSR are diffuse and those of quartzites and chalcedonies are both point and diffuse, whereas the secondary sources of all these toolstones are predominantly diffuse. These facts introduce variability in the form that scatter areas around each

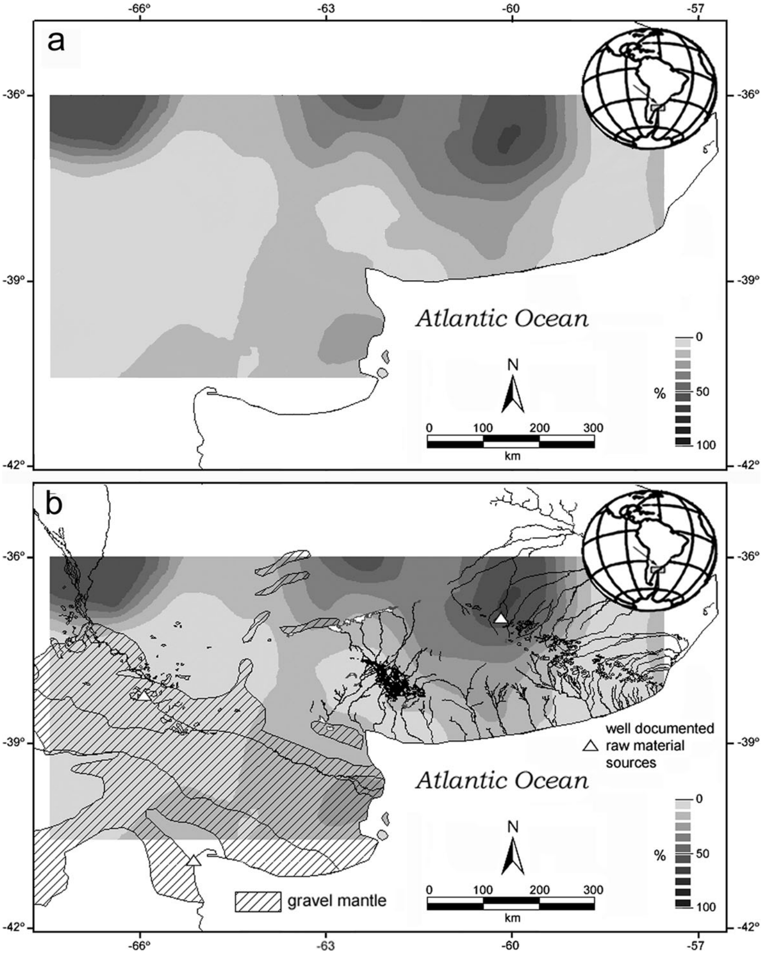

**Fig. 9** Continuous spatial model (raster map) of the lithic landscape of chalcedonies from east-central Argentina (relative frequency data); **a** without physiographic information; **b** with sources, water courses, and water bodies

source adopt. In the case of OSR, an irregularly shaped and extended scatter area tends to map onto the entire distribution of the major and minor mantles of the Patagonian Shingle Formation (Fig. 7). The highest percentage peak (60–70 %) is not constrained to a relatively small area, but it has a very wide spatial expression. This contrasts with

**Table 2** Standard error statistics associated to each continuous surface model (simple kriging, K-Bessel semivariogram)

| Toolstone class | Min | Max | Mean | Std. dev. | Median |
|---|---|---|---|---|---|
| OSR | 11.15 | 13.81 | 13.56 | 0.17 | 13.59 |
| Quartzites | 17.97 | 19.13 | 18.51 | 0.23 | 18.51 |
| Chalcedonies | 8.70 | 17.29 | 17.28 | 0.28 | 17.29 |

the distribution of the scatter area around the best described group of point sources of chalcedony, situated in the northwestern extreme of Tandilia (Sierras Bayas) (Barros 2009; Barros and Messineo 2004; Lozano 1991) (Fig. 9). In this case, such area has a somewhat subconical shape around the cluster of sources, at least between the range of 40 and 70 %, with a smaller and well-delineated maximum percentage peak area (60–70 %). Quartzites, in turn, have a more varied pattern of distribution of the scatter areas around the putative sources. In the center of the area, the highest frequency peak (70–80 %) occurs around the hills of Ventania and along the river basin of Sauce Grande-de las Mostazas, an area rich in both primary and secondary raw material sources of varied quality (Bayón and Zavala 1994; Catella *et al.* 2010). In the northeast, an even higher peak (90–100 %) is found well inside the Salado River depression which, in contrast with the first, is an area entirely devoid of known sources of these and other raw materials. In this case, however, the increasing SW-NE gradient in percentage values and the height of the peak are strongly influenced by the extremely low density of data points (Fig. 6), the border effect associated with the lack of samples located outside the study area, and the documented lack of raw material sources in the plains northeast from Tandilia. In this hilly range, the best known sources of high-quality quartzites (outcrops and secondary deposits of the Sierras Bayas Group, situated in the area of Barker-La Numancia; Colombo 2011, 2013) are included within an area of no particularly high percentage values (50–60 %) (Fig. 8), probably due to the competition with other good quality lithic raw materials (chalcedonies and silicified dolomites) whose main sources are within a maximum radius of about 100 km from these places (Barros 2009; Barros and Messineo 2004; Flegenheimer 1991; Fig. 9).

At this stage of the research, it is clear that the spatial models generated for each toolstone class have different heuristic value. In the case of OSR—whose sources are well known in terms of its location and extension but little known in terms of its internal variability in relation with key aspects such as visibility, accessibility, quality, and exploitability—the spatial models presented here can help to identify likely areas of preferential procurement (Fig. 7). This information can be used to design survey and sampling strategies aimed at improving the characterization of these diffuse sources. Regarding quartzites, while the knowledge about location and differential quality of the sources is acceptable, the relative contribution of each source to particular artifact assemblages is less known in the absence of a large-scale, technology-aided sourcing effort. The subconcentric distribution of the percentage intervals around Ventania (Fig. 8) allows establishing with any precision the likely area of influence of quartzites from primary and secondary sources distributed in and around these hills. This is important since it allows formulating hypotheses, on the basis of the geographical position of the recovered artifacts, about the likely origin of the quartzites represented, which can be further evaluated by applying different sourcing techniques. As for chalcedonies, finally, our spatial model (Fig. 9) is informative about the likely existence of not yet found sources distributed across the regional space. In this case, such information can be useful to guide and optimize both survey and sourcing efforts.

The last issue we want to discuss here refers to the reciprocal relationships between the three toolstone classes considered in this exploratory study. Figure 10 shows the modeled spatial continuous distribution of artifact assemblages in which one, two, or three of the measured rock classes are represented with percentage values equal or higher than 10 % (classification of data and superimposition of the resulting layers with

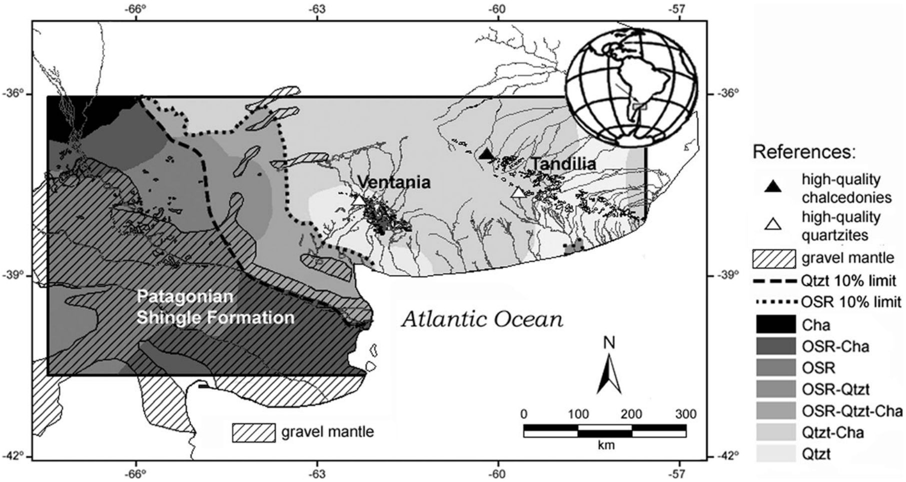

**Fig. 10** Modeled spatial continuous distribution of artifact assemblages in which the three rock classes are represented with percentage values equal or higher than 10 % (classification of data, superimposition and merging of layers with different degree of transparency)

different degree of transparency). Most of the Humid Pampas have a rather simple composition to the degree that most of the modeled surfaces correspond to areas dominated by either one or two toolstones (quartzites and quartzites-chalcedonies, respectively). In the Dry Pampas and northeastern Patagonia, the situation is more complex since in both regions there are areas dominated by one (OSR, chalcedonies), two (OSR-chalcedonies, OSR-quartzites), or three (OSR-chalcedonies-quartzites) rock classes. It is of particular interest the strip of land situated between the limits of 10 % OSR and 10 % quartzite, which has a uniform width of about 100 km and runs roughly parallel to the boundary between Humid Pampas and northeastern Patagonia in the south and Humid Pampas and Dry Pampas in the west. Within this area that encompasses the northern edge of the main outcrop of the Patagonian Shingle Formation as well as many other lesser gravel mantles of the same geological unit, the modeled surfaces combine principally two toolstones, OSR and quartzites. This zone allows for the examination of the reciprocal relationships between two groups of raw materials, one abundant in northern Patagonia and Dry Pampas—OSR—and other emblematic of the Humid Pampas—quartzites. In this regard, it is instructive to consider the shape of the respective fall-off curves as shown in Fig. 11. In this figure, we represented the curves of OSR and quartzites corresponding to two virtual transects drawn across the modeled surfaces with the aid of the ArcGIS 3D Analyst module. In general, the fall-off curves of both toolstones match the expected model of monotonic decline with increasing distance from the likely sources. In effect, in both cases, each peak in the respective distance decay curves coincides with the localization of either a major or minor putative source. Both curves tend to cross at points that are nearly equidistant from the major sources of OSR and quartzites (considering, in the latter case, the outcrops in the hills of Ventania and the pebble banks distributed along the streams that have their headwaters in these hills; Catella 2014). However, quartzites reach percentage values on or nearby their sources notoriously higher than those of OSR, thus implying that the effects of competition with alternative knappable materials at the

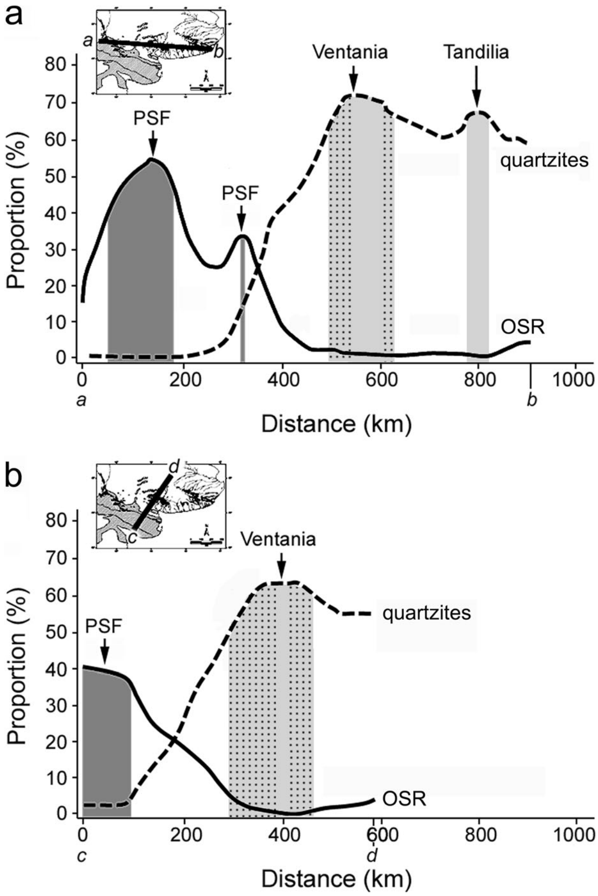

**Fig. 11** Fall-off curves (**a, b**) of OSR and quartzites (relative frequency data) corresponding to two virtual transects (*a–b* in **a** and *c–d* in **b**) drawn across the modeled lithic landscapes The *vertical stripes* represent the position and extension of the potential sources of each toolstone class (OSR: *dark gray*; quartzites, primary sources: *light gray*; quartzites, secondary sources: *light gray with dots*)

sources are higher for OSR than for quartzites. In fact, as it was already mentioned, the main sources of OSR are the gravel deposits of the Patagonian Shingle Formation, composed of a relatively high variety of potential toolstones. In contrast, in Ventania—where the outcrops and most of the secondary deposits of quartzites are placed—there are fewer alternative raw material sources, being those of rhyolites and silicified limestones the most prominent among them (Catella 2014; Moirano 1999; Oliva and Moirano 1997), although the spatial distribution of artifact made on these stones is rather restricted (Barros 2009; Catella 2014; Moirano 1999; Oliva and Moirano 1997), thus suggesting that they have played a secondary role in the subsistence of Pampean populations through time. The construction of specific gravity models (Wilson 2007b) is an urgently needed task in order to test for this and other hypotheses about competitive interactions between different raw materials and sources.

Summarizing, we can say that the case study presented in this paper reveals the potential of the proposed approach for the archaeological study of lithic landscapes.

Even in situations where the quality of the information about the total range of variability in both raw material sources and artifact assemblages is less than perfect and the particularities of the links between the two are yet not well known, the production of spatial continuous models can make a valuable contribution to the enhancement of our knowledge about distributional aspects of the regional lithic record. However, it is clear that in order to discuss spatial patterning in terms of the long-term effects of behavior and organization, a continuous feedback between spatial modeling and the acquisition of increasingly detailed information about lithic sources (*e.g.*, distribution, visibility, accessibility, exploitability) and archaeological assemblages (*e.g.*, distribution, composition, technology) is needed.

## Concluding Remarks

The aim of this paper has been to introduce the concept of lithic landscape (which is, strictly speaking, a redefinition of a term already present in the literature; Gould and Saggers 1985, p. 124) and discuss what we consider the proper methodology for its modeling and study. The application of such a concept and methodology to the analysis of a specific case study helped to identify the strengths and weaknesses of the advocated approach.

Among the strengths, we can mention the ability of continuous spatial models to integrate, in a coherent picture, information that is widely scattered and inarticulate. In particular, the use of geostatistical tools for characterizing the spatial variation in quantitative data collected at georeferenced point locations allows for the creation of interpolated continuous surfaces together with estimated uncertainty in those surfaces. Through this procedure, it is possible to overcome, to some extent, the limitations imposed by the distribution of the spatial data (*e.g.*, clustering, anisotropies). Within a GIS framework, the generated surface maps can be compared with each other and with different spatial datasets containing environmental and/or paleoenvironmental information about topography, hydrology, soils, or other relevant variables. This enables to investigate the reciprocal relationships between two or more raw materials and sources (a mostly neglected issue), as well as to assess the influence of landscape features on the form (*i.e.*, size, shape) of the structural units identified in the modeled lithic landscapes. Another advantage of the continuous surface model applied to the study of the distribution of different toolstones is its ability to detect, on the basis of spatial differences in the value of the response variable, zones where the location of not yet discovered sources is more likely. This is important information that can guide the search for such sources.

The principal weakness of the proposed approach is the lack of control of field sampling procedures at the spatial scales in which it is usually meaningful to talk about lithic landscapes (*i.e.*, meso- to macroscale). To the extent that it is extremely difficult for a single research project to develop fieldwork in such a wide scale, it is likely that quantitative and distributional data about several aspects of the lithic record will come from a heterogeneous combination of survey strategies deployed at different times by different research teams. This major drawback undoubtedly affects the quality of data available to model lithic landscapes. However, the continuous surface maps of the kind presented here, despite being based on imperfect (albeit perfectible) information, have the potential to guide future survey and sampling efforts in a more problem-oriented way.

As a final thought, we would like to emphasize that the importance of a proper description and analysis of the spatial structure of lithic landscapes resides in the fact that it is the needed baseline from which to formulate and assess different explanatory models (a long-term effort and something that we are just beginning to work on) about their underlying generative mechanisms, explicitly addressing the problem of equifinality and acknowledging—and taking advantage of—the palimpsest nature of the lithic record. It is precisely the development of an integrated approach based on the iterative interplay between empirical data, spatial modeling, and theory building *via* simulative experimentation within a coherent explanatory framework the true research challenge for the next years.

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